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CONTENTS

Page

Illumination from Sources of Large Area, by P. Hartill, A.M.I.E.E. *(Fellow)* - 253

Activities of Centres - - - 265

Sessional Meeting in London - - 266

Additions to List of Members - 266

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ILLUMINATION FROM SOURCES OF LARGE AREA*

By P. HARTILL, A.M.I.E.E. *(Fellow)*

As the science of illuminating engineering develops, the technical equipment of the illuminating engineer must be extended to deal with new problems as they arise. Simplified methods are desirable in dealing with these problems. It is, however, necessary to understand the significance and limitation of empirical formulae, and to recognise circumstances that may lead to qualification of general and accepted principles.

In the early days of illuminating engineering it was usual, in planning lighting installations, to predetermine values of illumination by the "point to point" method, often a somewhat lengthy and laborious process. The introduction of the familiar lumen method for computing average values of illumination greatly simplifies such work. Yet it does not exempt the designer from the necessity of being familiar with fundamental principles and with the application of the inverse square and cosine laws—more especially when it is desired to know not the *average* illumination but the illumination at some specific point, which the lumen method does not determine.

In practice, however, even such fundamental laws as those quoted above need to be interpreted with care. For a strictly point source the inverse square law applies rigidly, but it does not apply with the same precision to sources of considerable area, even though it does still apply with substantial accuracy to small individual components thereof.

Similarly, when we pass from the consideration of illumination to brightness (variously measured in terms of "candles per square inch," "candles per square foot," or "equivalent foot-candles") it is well to recall that in practice few surfaces act as perfect diffusers, though a near approach may be found in a uniformly clouded sky, a blue sky (apart from the sun itself), and a well-designed laylight. The use of the familiar "daylight factor" as a measure of the proportion of unrestricted outside daylight entering an interior is based on the supposition that light coming from a uniformly white sky is completely diffused.

Daylight Factor.

In designing buildings the term "Daylight Factor" is used by architects to denote the ratio of the illumination at a point on a horizontal plane, produced by daylight through the windows, to the illumination produced by the whole hemisphere of a uniformly bright sky if it were visible from the point in question. Evidently, if a room were constructed entirely of perfectly transparent windows, the daylight factor at any point in the room would be 100 per cent. In the case of a room where the window area is comparatively small, the daylight factor is, of course, considerably less than 100 per cent. and varies at different points on the working plane depending upon the relative position of the window.

The main object of this paper is to describe a simplified method of determining what size of window or windows should be provided to ensure a re-

*Paper originally delivered at a Sessional Meeting of Birmingham Centre in July, 1941, and later at Cardiff, Leeds and Manchester.

quired daylight factor. It is clear that the same method can also be used for calculating illumination values produced by artificial windows or laylights.

One of the primary questions to be considered is the relation between the brightness of a uniformly overcast sky and the illumination produced by it. In order to investigate this relationship consider a miniature sky in the form of a hemispherical dome, whose interior brightness is the same as that of the sky, surrounding the point at which the illumination is to be measured. The value of the illumination within the dome would be the same if the dome were perfectly transparent so as to admit the total radiation from the sky. If the sky or dome has uniform brightness and behaves like a perfect diffuser, that is, if it has the same appearance in every direction, it follows that the rate of light emission from any part of it is also uniform; moreover, since all that can be seen in any direction from a point on the horizontal plane within the dome is this uniform brightness, light must be received at this point at the same rate at which it is emitted. In other words the illumination in foot-candles at the point in question is numerically equal to the luminosity of the sky in equivalent foot-candles, each of these terms being another name for the light-flux-density in lumens per square foot.

If only a comparatively small portion of the dome is luminous, or, to put it another way, if only a small area of the sky is visible, the remainder being entirely blacked out, the value of the illumination within the dome varies from point to point on the horizontal plane, depending upon the relative position of the luminous portion. Consider a room, having a window in one wall and a point on a horizontal plane where it is required to find the daylight factor. The light reaching this point through the window is contained in a pyramid of rays, and an imaginary hemisphere centred at the point, that is, at the apex of the pyramid. It is therefore possible to forget the window and concentrate on the hemisphere which can be considered as entirely blacked-out except for the area representing the projection of the window; this can be regarded as a luminous portion of the spherical surface of the same brightness as the sky. The ratio of this projected area to the area of the whole hemispherical dome is the proportion of the whole sky illuminating the point in question, but, owing to the cosine law, the value of the horizontal illumination at this central point varies dependent upon whether the luminous portion of the dome is nearer to the zenth or the horizon. In this connection the following important fundamental principle (the methematical development of which is illustrated in an appendix to this paper) may be quoted:—

The horizontal illumination at the geometric centre of a hemispherical dome is proportional to the area of the re-projection of the luminous portion of the dome on the horizontal plane.

The magnitude of this re-projected area can be seen by viewing the dome in plan. The actual value of the illumination is found by measuring this area in square units, when the radius of the hemisphere is one unit, and multiplying by the brightness of the luminous portion in candles per square foot. This principle is true of any light source, whatever its size, shape or orientation, provided that its brightness is sensibly uniform.

Windows and Laylights.

In the majority of cases one has to deal with rectangular windows or laylights which are located vertically in walls or horizontally in ceilings, and there exist rigid formulae for the treatment of such sources. As this is the most usual problem encountered in practice, the application of the author's graphical method to a rectangular area is illustrated—though it is to be understood that

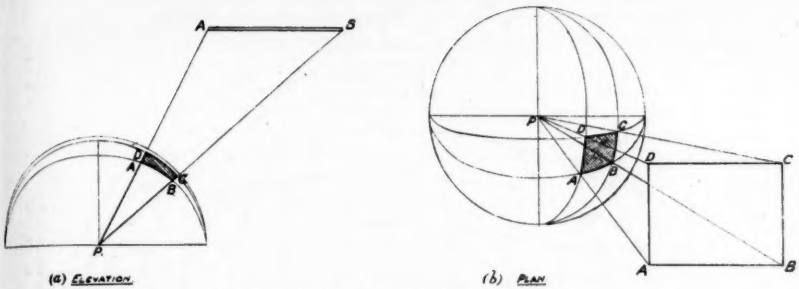


Fig. 1. Projection of a rectangle on a hemisphere.

the method is in fact applicable to a luminous area of any prescribed dimensions and shape. From an examination of the projection of a rectangle on to a hemispherical dome by means of the pyramid of light method it is obvious that the projection of the straight line forming one side of the rectangle is an arc of a great circle, that is, a circle concentric with the hemisphere and described on its surface. If the four sides of the rectangle are each produced in both directions to infinity, their projections are four semicircles whose intersection forms the required projected area of the rectangle. (Fig. 1.) These lineal projections, or semicircles, are similar to lines of longitude on a model of the world, but while the world is usually marked with lines of longitude and latitude, here we have two sets of longitudinal lines converging at the poles of two axes at right angles to each other. It is as though the world had not only North and South poles but also East and West poles. (Fig. 2.) On a model of the world it is a simple matter to plot the position of a ship or town if the degrees of latitude and longitude are known. In the same way, if we have a sphere marked with two sets of longitude lines at given angular intervals from their respective meridians, any point can be located by the measuremnt of two angles. Degrees of latitude and longitude can also be used to indicate the direction of an object remote from the surface of the earth, such as an aeroplane. Even the direction of the moon or a star could be so indicated, although in astronomy the angles of declination and right ascension are used for this

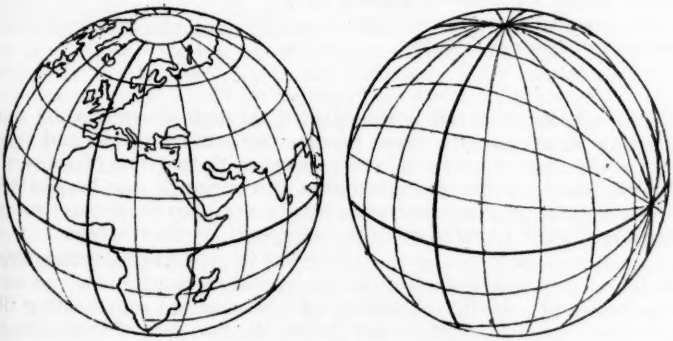


Fig. 2. Bipolar and quadripolar spheres.

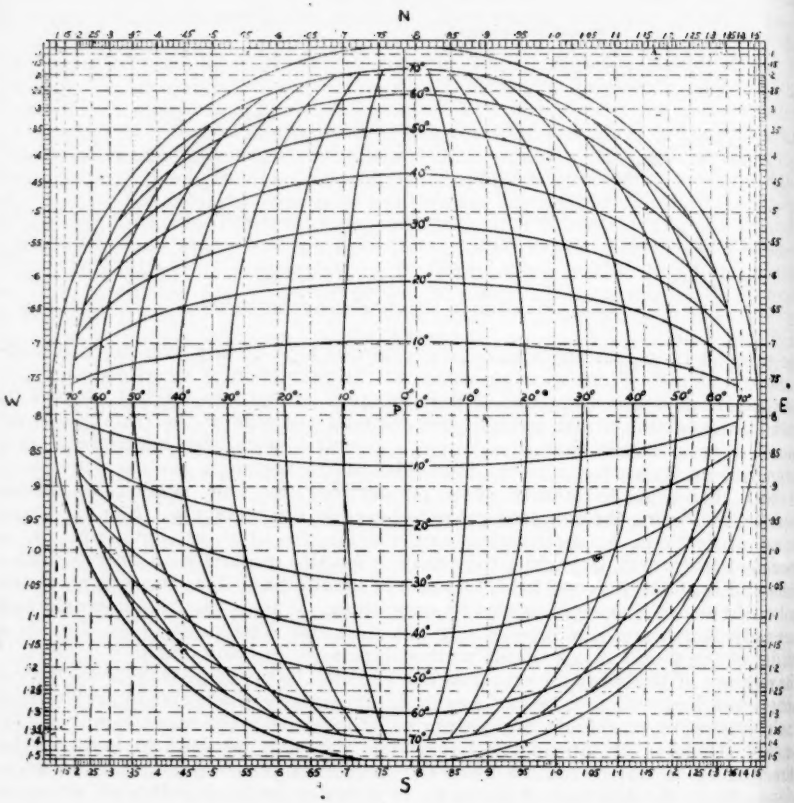
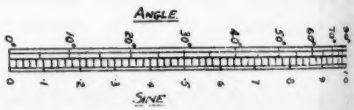


Fig. 3. Web diagram for computing daylight factor from horizontal skylights, or illumination from horizontal laylights.



purpose. All points on a radial line drawn through the centre of the earth and extending outwards into space possess the same latitude and longitude. Similarly, in the case of a hemisphere marked with two sets of lines of longitude, the four corners of the projected area of a rectangle can be plotted on its surface by the same angular measurements as are used to denote the position of the rectangle itself in relation to the centre of the hemisphere.

In practice this principle of projection on to an imaginary hemisphere of unit radius and re-projection on to the horizontal working plane can be easily applied by means of a specially constructed web diagram representing the plan view of the hemisphere, on which are drawn the two sets of longitudinal lines at equal angular intervals. (Fig. 3.) The manner in which this diagram can

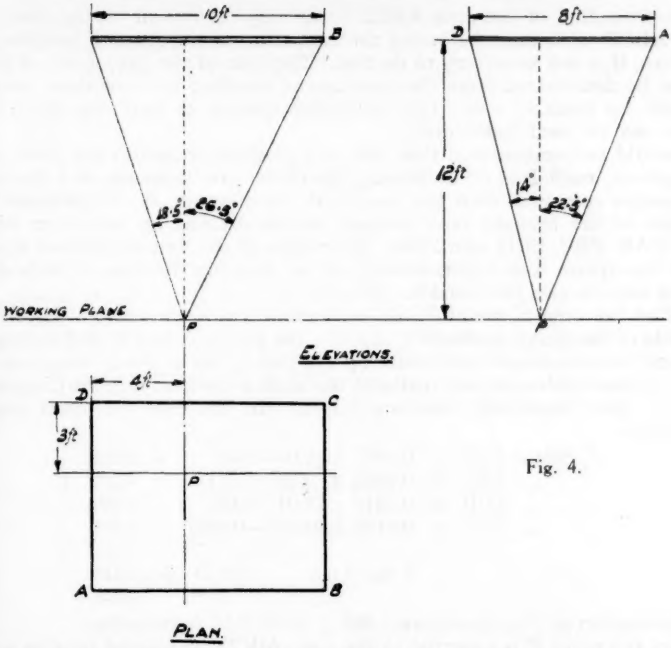


Fig. 4.

be used to measure the required projected area is, perhaps, best explained by means of an actual example.

EXAMPLE I.

Suppose it is required to determine the values of horizontal illumination at three points on a working plane, produced by a horizontally mounted rectangular laylight, measuring 10 ft. by 8 ft., of brightness 20 candles per square foot, fixed at a height of 12 ft. above the working plane. (See Figs. 4, 5, and 6.)

First of all it is necessary to consider the web diagram as laid horizontally on the working plane, its centre, P, coinciding with the point at which the illumination is to be measured, and its N—S and E—W axes lying respectively parallel to two adjacent sides of the laylight. Taking each corner of the laylight in turn, its projection on the diagram can be plotted by two angular measurements, just as the latitude and longitude of an aeroplane, or of some remote point in space, would be indicated on a map of the earth. This can be done by viewing the laylight, and the point on the working plane in elevation (a) looking along the N—S axis, and (b) looking along the E—W axis. Four angles can thus be measured between the perpendicular through P and each of the four sides of the laylight. Each corner can then be located by selecting the appropriate pair of angles and plotting with respect to points of the compass. Calling the four corners A, B, C, D, and referring to Fig. 4, their positions on the web diagram are as follows:—

A	18½° W	22½° S
B	26½° E	22½° S
C	26½° E	14° N
D	18½° W	14° N

The projection of the area ABCD could now be drawn on the diagram by joining ABCD with lines following the curvature of the lines of longitude, but, in practice, *it is not necessary to do this.* The area of the projection of the laylight can be determined from the positions of the four corners alone, and these need only be marked with light pencilled crosses so that one print of the diagram can be used indefinitely.

It should be remembered that this web diagram indicates the plan view of a hemisphere; each line of longitude, therefore, now appears as a half-ellipse whose centre coincides with the centre of the diagram, P. Consequently, the projection of the laylight now plotted can be divided up into four elliptical sectors, PAB, PBC, PCD, and PDA. By means of the figures marked along the sides of the square web superimposed on the diagram the area of each of these elliptical sectors can be found as follows:—

To find the area of sector PAB, for example, note the two values along the South side of the diagram directly opposite the points A and B, and *multiply the difference between these two values by the sine of the angle of longitude of the side AB.* If sine tables are not available the scale accompanying the diagram may be used to give reasonably accurate results. In this case the areas work out as follows:—

Sector PAB	= 0.3827 x (1.0—0.64)	=	0.138
„ PBC	= 0.4462 x (0.96—0.67)	=	0.130
„ PCD	= 0.2419 x (1.01—0.63)	=	0.092
„ PDA	= 0.3173 x (0.975—0.665)	=	0.098
	Total Area ABCD	=	0.458

The illumination at P is therefore $0.458 \times 20 = 9.16$ foot-candles.

When the point P is external to the area ABCD, as viewed in plan, a slight modification of this procedure is necessary. Referring to Fig. 5, the bearings of the four corners are as follows:—

A	51½° W	22½° S
B	22½° W	22½° S
C	22½° W	14° N
D	51½° W	14° N

When these four points are plotted on the web diagram it is clear that the area ABCD is now the sum of elliptical sectors PAB, PDA, and PCD, *minus* sector PBC.

Sector PAB	= 0.3827 x (0.6 —0.36)	=	0.092
„ PDA	= 0.7826 x (0.91—0.71)	=	0.157
„ PCD	= 0.2419 x (0.59—0.35)	=	0.058
	Total	=	0.307
„ PBC	= 0.3827 x (0.965—0.62)	=	0.132
	Area ABCD	...	0.175

The illumination at P is therefore $0.175 \times 20 = 3.5$ foot-candles.

In Fig. 6 the bearings of the four corners are as follows:—

A	51½° W	22½° N
B	22½° W	22½° N
C	22½° W	47½° N
D	51½° W	47½° N

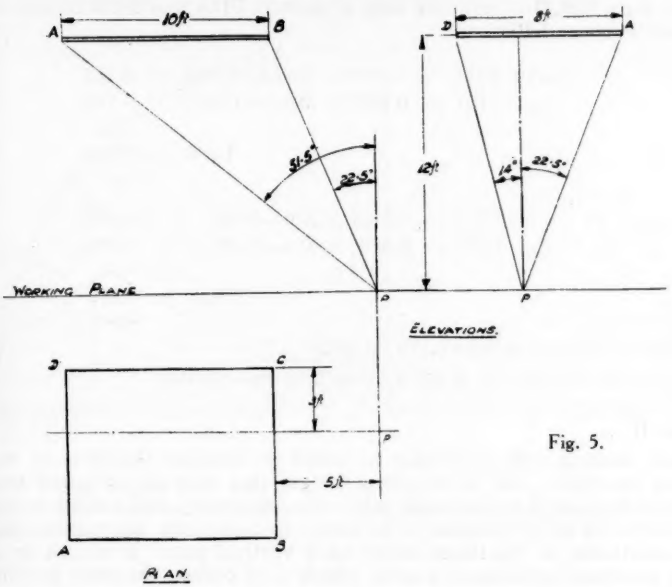

10ft
A
B
8ft
D
A
51·5°
22·5°
12ft
14°
22·5°
WORKING PLANE
P
P
ELEVATIONS.
D
C
3ft
P
5ft
A
B
PLAN.

Fig. 5.

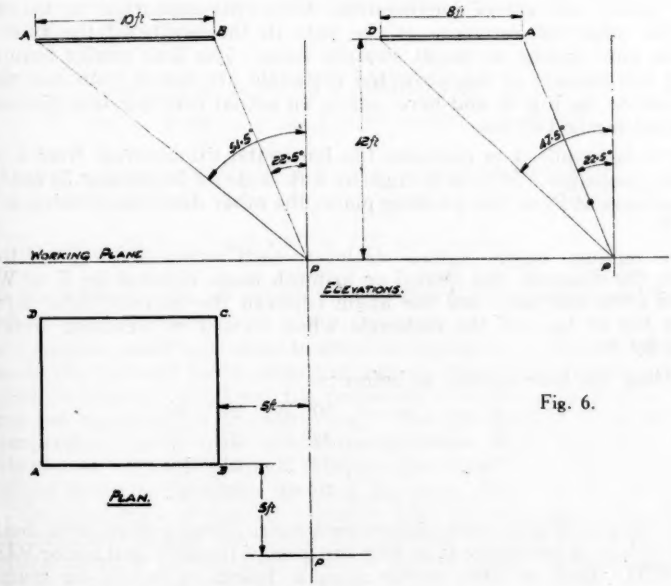

10ft
A
B
8ft
D
A
51·5°
22·5°
12ft
47·5°
22·5°
WORKING PLANE
P
P
ELEVATIONS.
D
C
5ft
A
B
PLAN.
3ft
P

Fig. 6.

The area ABCD is now the sum of sectors PDA and PCD minus the sum of sectors PAB and PBC.

Sector PDA	= 0.7826 x (0.655—0.485)	=	0.133
,, PCD	= 0.7373 x (0.65 —0.43)	=	0.162
	Total	=	0.295
,, PAB	= 0.3827 x (0.6—0.36)	=	0.092
,, PBC	= 0.3827 x (0.6—0.39)	=	0.080
	Total	=	0.172

$\therefore$ Area ABCD = 0.295—0.172 = 0.123.

$\therefore$ Illumination at P = 0.123 x 20 = 2.46 foot-candles.

EXAMPLE II.

When dealing with vertically mounted rectangular laylights or windows the same procedure can be followed, but in this case the required projected area to be measured is that seen when the imaginary unit-radius hemisphere is viewed in elevation instead of in plan. In this view, the projected area is also proportional to the illumination on a vertical plane produced by a horizontally mounted rectangular source, which is, of course, the same as horizontal illumination from a vertical source. [See Fig. 1(a).]

The web diagram (Fig. 7), representing the required view of the hemisphere, shows one set of longtitudinal lines still appearing as half-ellipses, while the other set converge at the pole in the centre of the base of the web and now appear as radial straight lines. The four angles required for plotting the corners of the projected rectangle are found from one plan and one elevation, as Fig. 8, and here, again, an actual example best demonstrates the correct method of use.

Let it be required to calculate the horizontal illumination from a vertical luminous rectangle ABCD, 6 ft. high by 8 ft. wide, of brightness 30 candles per sq. ft., at a point P, on the working plane, the other dimensions being as shown in Fig. 8.

Two angles again suffice to locate each corner of the projected rectangle on the diagram, the lateral or azimuth angle denoted by E or W being obtained from the plan, and the angle between the perpendicular through P and the top or base of the rectangle when viewed in elevation (side view), denoted by N.

Plotting the four corners as before:—

A	50° W	27° N
B	22° E	27° N
C	22° E	51½° N
D	50° W	51½° N

The area ABCD is now determined more simply than with horizontal sources; it is only necessary to deduct the area of the elliptical sector PAB from sector PCD. Each of these sector areas is found, as before, by multiplying

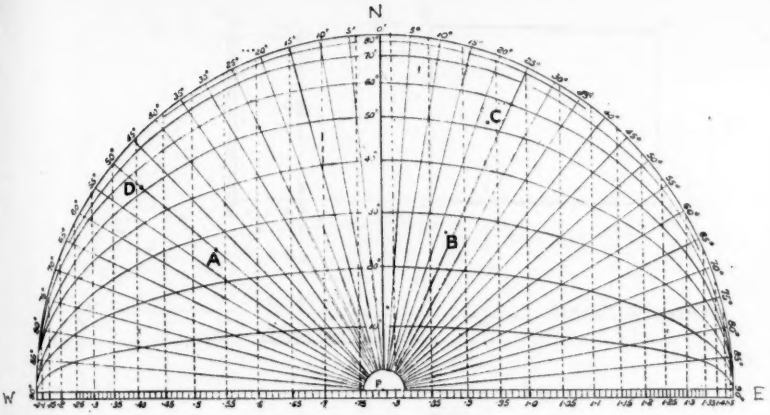
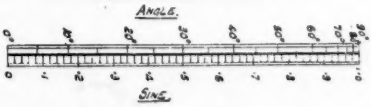


Fig. 7. Web diagram for computing daylight factor from vertical windows, or illumination from vertical laylights.



the difference between the two values marked opposite A and B, or C and D, along the base of the diagram by the sine of the angle of longtitude locating the elevation of **AB** or **CD**.

$$\text{Sector PCD} = 0.7826 \times (0.93 - 0.405) = 0.411$$
$$\text{,, PAB} = 0.454 \times (0.87 - 0.535) = 0.152$$
$$\text{Total} = 0.259$$

$\therefore$ Illumination at P $= 0.259 \times 30 = 7.77$ foot-candles.

This procedure covers all cases of horizontal illumination from vertically mounted rectangular sources.

The examples given here refer to artificial laylights of a known brightness. To estimate the daylight factor, obtained with horizontal rectangular skylights or vertical rectangular windows, the projected areas must be plotted on the diagrams and measured in the same way. The illumination from the whole sky is proportional to the total area of the plan view of the hemisphere. This is a circle of area πr^2, which equals π when the radius $r = 1$, and consequently the daylight factor is found by dividing the area of the projected rectangle by π. The total area of the semicircular web diagram represents the illumination from one half of the whole sky, and the ratio of the projected area of a vertical window to this gives what is known as the "Sill Ratio" which is twice the value of the daylight factor.

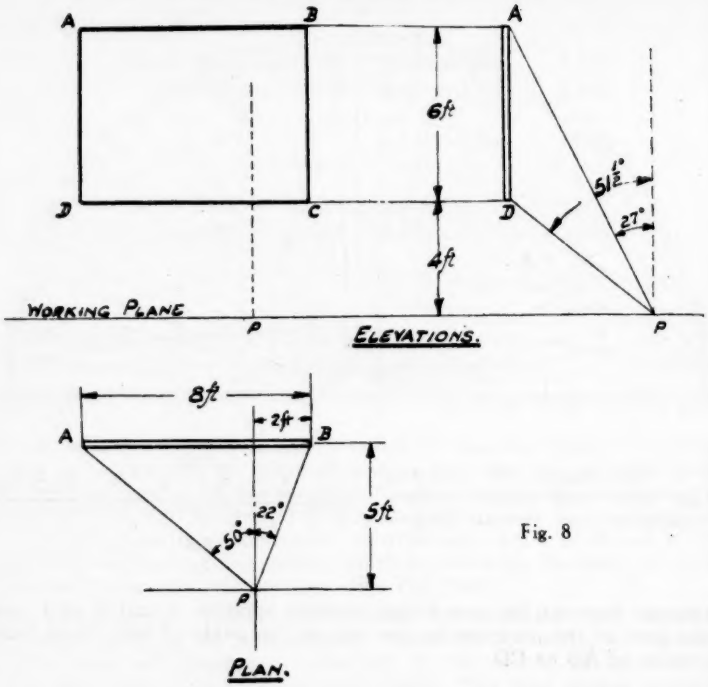


Fig. 8

Appendix 1. Construction of Web Diagrams

The diagram representing the plan view of the unit-radius hemisphere, for measuring the projected areas of horizontally mounted luminous rectangles or skylights, may be constructed as follows:—

Referring to Fig. 9, describe a circle, centre P, of reasonable diameter, say 10 inches, and draw the two axes, NS and EW at right angles to each other. To plot an elliptical line such as WME, representing longtitude θ°N, for example, mark off the point M on PN so that PM/PN = sin θ. The trace of the ellipse is such that if any line is drawn parallel to NS, intersecting the EW axis at p, the elliptical line at m and the circumference of the circle at n, the ratio pm : pn always equals sin θ. The position of M can be found graphically by marking the point K on the circumference of the circle, so that $\angle$ KPE = θ, and drawing KM parallel to EW. Reasonable accuracy can be obtained if the elliptical lines are drawn to denote intervals of 10° on the surface of the hemisphere.

The superimposed square web consists of two sets of dotted lines drawn parallel to the NS and EW axes respectively. Two such lines, GH and JL, are shown in Fig. 9. These intersect the circumference of the circle in Q and R and the appropriate value to be marked along the sides of the square is half the angle QPW, or RPW, in radians. Suitable intervals for these lines can be established by marking a series of points on the semicircular arc WNE, at angular separations of one-tenth of a radian (i.e., about 5.73°) from W, and drawing lines through these points parallel to NS. This process should then be repeated for the semicircular arc NES, measuring intervals of one-tenth of a radian from N, and this time the lines must be drawn parallel to EW.

The semicircular web for measuring the projected areas of vertical rectangles has only one set of elliptical lines and one set of dotted lines parallel to PN,

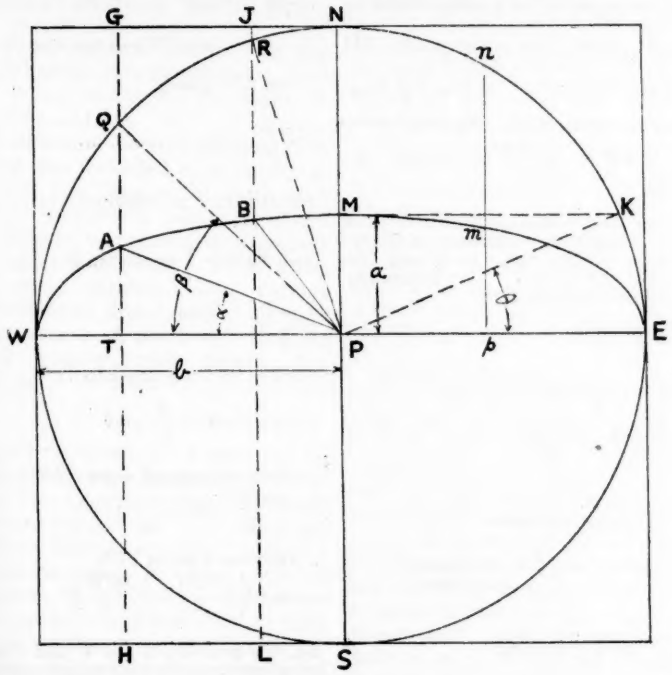


Fig. 9.

drawn in the same manner as in the first diagram. The projections of vertical sides of rectangles now lie along radial lines from P, a series of which are drawn at equal angular intervals.

Appendix II. Principle of Unit-radius Hemisphere

Consider an elemental area dA of a spherical surface. Then, if the brightness of the surface is B, the candle-power of this element directed towards the centre P is B.dA. If the element is infinitesimal, so that it may be regarded as a point, its contribution towards the horizontal illumination at P is B.dA cos ϕ/r^2 by the inverse square and cosine laws, ϕ being the angle of incidence at P and r the radius of the hemisphere. When r = 1 foot the illumination is therefore B.dA cos ϕ foot-candles. By simple trigonometry, the projection, or plan-view, of the element dA on the horizontal plane is dA.cosϕ, which, when multiplied by B, gives the same result. It follows that the horizontal illumination at P due to any area of the spherical surface is Σ B.dA.cos ϕ, which is found by measuring the total projected area on the horizontal plane.

Appendix III. Area of Sector of Ellipse

The elliptical line, WME in Fig. 9, forms a half-ellipse whose centre is at P, PM being the minor radius and PW the major radius. The area of a sector of the ellipse bounded by the major radius PW and any other radius, such

as PA, can be found by a simple formula derived as follows:—

Let the minor and major radii, PM and PW, be a and b respectively.

Let any other radius, such as PA, be r.

Then, by integration, the area of the sector $PAW = \int \frac{r^2 \, d\alpha}{2}$, where $\alpha = \angle APW$.

The line GH, drawn parallel to NS and passing through A, intersects the circumference of the circle in Q and the major radius PW in T. The properties of an ellipse are such that

$$\left(\frac{AT}{a}\right)^2 + \left(\frac{PT}{b}\right)^2 = 1$$

Now, $AT = r \sin\alpha$ and $PT = r \cos\alpha$

$$\therefore \quad \frac{r^2 \sin^2\alpha}{a^2} + \frac{r^2 \cos^2\alpha}{b^2} = 1$$

$$\therefore r^2 = \frac{a^2 b^2}{b^2 \sin^2\alpha + a^2 \cos^2\alpha}$$

but the radius b = 1 (unit-radius of hemisphere)

$$\therefore r^2 = \frac{a^2}{\sin^2\alpha + a^2 \cos^2\alpha}$$

$$\therefore \text{Sector area PAW} = \frac{a^2}{2}\int \frac{d\alpha}{\sin^2\alpha + a^2 \cos^2\alpha}$$

$$= \frac{a}{2} \arctan \frac{\tan\alpha}{a} \quad \ldots\ldots (1)$$

Let $\angle QPW = \beta$

then $QT = \sin\beta$ (since $PQ = 1$)

and $\frac{AT}{QT} = \frac{PM}{PN} = a$ (see appendix 1)

$$\therefore AT = r \sin\alpha = a \sin\beta$$

also $PT = r \cos\alpha = \cos\beta$

$$\therefore \tan\alpha = a \tan\beta$$

$$\therefore \frac{\tan\alpha}{a} = \tan\beta \quad \ldots\ldots\ldots\ldots (2)$$

Substituting in equation (1):—

$$\text{Area PAW} = \frac{a}{2} \arctan \tan\beta$$

$$= \frac{a}{2} \cdot \beta$$

but $a = \sin\theta$ (see appendix 1)

$$\therefore \text{Area PAW} = \frac{\beta}{2} \cdot \sin\theta$$

Similarly the area of sector PBW

$$= \frac{\angle RPW}{2} \cdot \sin\theta$$

$$\therefore \text{the area of sector PAB} = \sin\theta\left(\frac{\angle RPW}{2} - \frac{\angle QPW}{2}\right)$$

i.e., the product of $\sin\theta$ and the difference between the two values appropriate to the lines GH and JL indicated along the North or South sides of the square diagram.

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The Illuminating Engineering Society is not, as a body, responsible for the opinions expressed by individual authors or speakers.

With a view to avoiding possible confusion with other publications, reference to these Transactions should be in the form :—" Trans. Illum. Eng. Soc. (London)."

ACTIVITIES OF CENTRES

BATH AND BRISTOL CENTRE. At the opening meeting on November 1, held in the Grand Hotel, the President repeated his address. Mr. L. C. Rettig, chairman of the Centre, presided. The meeting was preceded by a luncheon, at which the Mayors of Bath and Bristol were present, following which those present were invited to inspect a miniature exhibition. Fluorescent lamps were exhibited and various demonstrations illustrating their uses were arranged. A chart recording the various papers read before the Centre since its inception was also on view.

CARDIFF CENTRE. At a meeting of the Cardiff Centre on October 10, at which the chairman, Mr. T. Scott Harrison, presided, Mr. W. J. Jones delivered an address entitled "Lighting Through the Ages." Mr. Jones pointed out that as the result of extensive research carried out in this country, light was now produced at the cost of 700 candle-hours per penny compared with 80 candle-hours per penny in 1920. He also mentioned that in 1939 this country had more miles of first-class electric street lighting by discharge lamps than the rest of the world put together. This meeting was held in the Swansea Guildhall, where the Mayor of Swansea welcomed the Society to that city.

At a further meeting held in Cardiff on November 6, Mr. R. A. Eshelby presented a paper entitled "Day-Night Flying." The audience, which numbered approximately 90 persons, included a number of R.A.F. officers and A.T.C. cadets. A good discussion ensued.

HUDDERSFIELD GROUP. In presenting his chairman's address entitled "Television," on October 8, Mr. J. T. Thornton said that though the subject was perhaps somewhat unusual for a meeting of illuminating engineers, it was by no means outside their province. He then went on to explain the principles of television and the cathode ray tube, presenting highly technical points in a simple and interesting manner. On taking the chair, Mr. Thornton proposed a vote of thanks to Mr. E. Lunn, the retiring chairman, in reply to which Mr. Lunn thanked members for their support and appealed to younger members to take a more active part in the activities of the Group.

The second meeting of the Huddersfield Group during the present session took place on November 5, when Mr. W. T. F. Souter delivered a lecture entitled "Church Lighting." Pointing out the importance of retaining the ecclesiastical atmosphere of churches when designing lighting schemes, Mr. Souter said that though churches were often similar in many respects, after careful consideration it was usually found that each church had some feature in its design which called for specialised attention. The Archdeacon of Halifax, who joined in the ensuing discussion, said that there was a great deal that could be done, and must be done, to improve lighting in churches. He recalled cases where churches had been spoiled by unsuitable lighting systems.

NOTTINGHAM CENTRE. "High Voltage Fluorescent Light Sources" was the title of a paper given before the Nottingham Centre on November 1 by Mr. H. G. Jenkins and Mr. J. N. Bowtell. The authors described fluorescent lighting as the most significant development in the lighting field since the invention of the metal filament lamp, and traced its development from 1933 to the recently introduced high voltage, hot cathode fluorescent lamps. A vote of thanks to the authors was proposed by Professor H. Cotton.

SESSIONAL MEETING IN LONDON

A joint meeting took place with the Royal Institute of British Architects at 66, Portland-place, London, W.1, at 5.45 p.m., on Wednesday, November 6, 1946, when the chair was taken by Mr. C. G. Stillman, Vice-President of the R.I.B.A.

After the chairman had extended a cordial welcome to I.E.S. members and the President (Mr. J. S. Dow) had returned thanks, a paper entitled "New Lighting for Old Buildings" was presented by Mr. E. H. Penwarden and Mr. S. Anderson, in the course of which the authors discussed some of the reasons for the improvement of artificial lighting in old buildings, and suggested various methods of treatment co-ordinating the requirements of the architect and the illuminating engineer.

The ensuing discussion was opened by Dr. S. English, who was followed by Mr. E. B. Sawyer, Mr. Alister MacDonald, Mr. J. C. Lowson, and Mr. W. E. Rawson-Bottom. After Mr. Anderson had briefly replied to the discussion, the meeting was terminated by a vote of thanks to the authors.

Additions to List of Members

The following applicants have been duly elected by the Council to membership in the Society, and their names have been added to the list of members:—

SUSTAINING MEMBERS:—

The Urban District Council of Hoylake.. *Representative*: Mr. R. M. Gravett.
The Electricity Works, Carr Lane, Hoylake, Wirral, CHESHIRE.

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COUNTRY MEMBERS:—

Neale, R. D. ..... School of Engineering, Canterbury University College, Christchurch, C.1, NEW ZEALAND.

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